

Synchrotron-Based Proton Driver and 2-MW Main Injector Upgrade

W. Chou

November 19, 2003

Presentation to the AAC Meeting, Nov 19-21, 2003 at Fermilab

Director's Commitment

“... I will do everything in my power to advance the neutrino physics case and the Proton Driver R&D over the next two years.”

Mike Witherell in an e-mail on Oct 10, 2003

Two Simple Facts

- ◆ Every large HEP lab has an accelerator project but Fermilab:
 - CERN: LHC
 - KEK/JAERI: J-PARC (US \$1.3B equiv.)
 - DESY: X-FEL (€700M)
 - GSI: Future ion facility (€700M)
 - SLAC: LCLS (\$220M)
 - Fermilab: ?
- ◆ On the recently published DOE's 28-facility list for the next 20 years, there are 4 HEP projects. Among them, proton driver is Fermilab's obvious choice for a secured future:
 - JDEM: Non-accelerator
 - BTeV: Detector project can't shoulder Fermilab's future
 - Linear Collider: Insecure
 - Super neutrino beam - proton driver

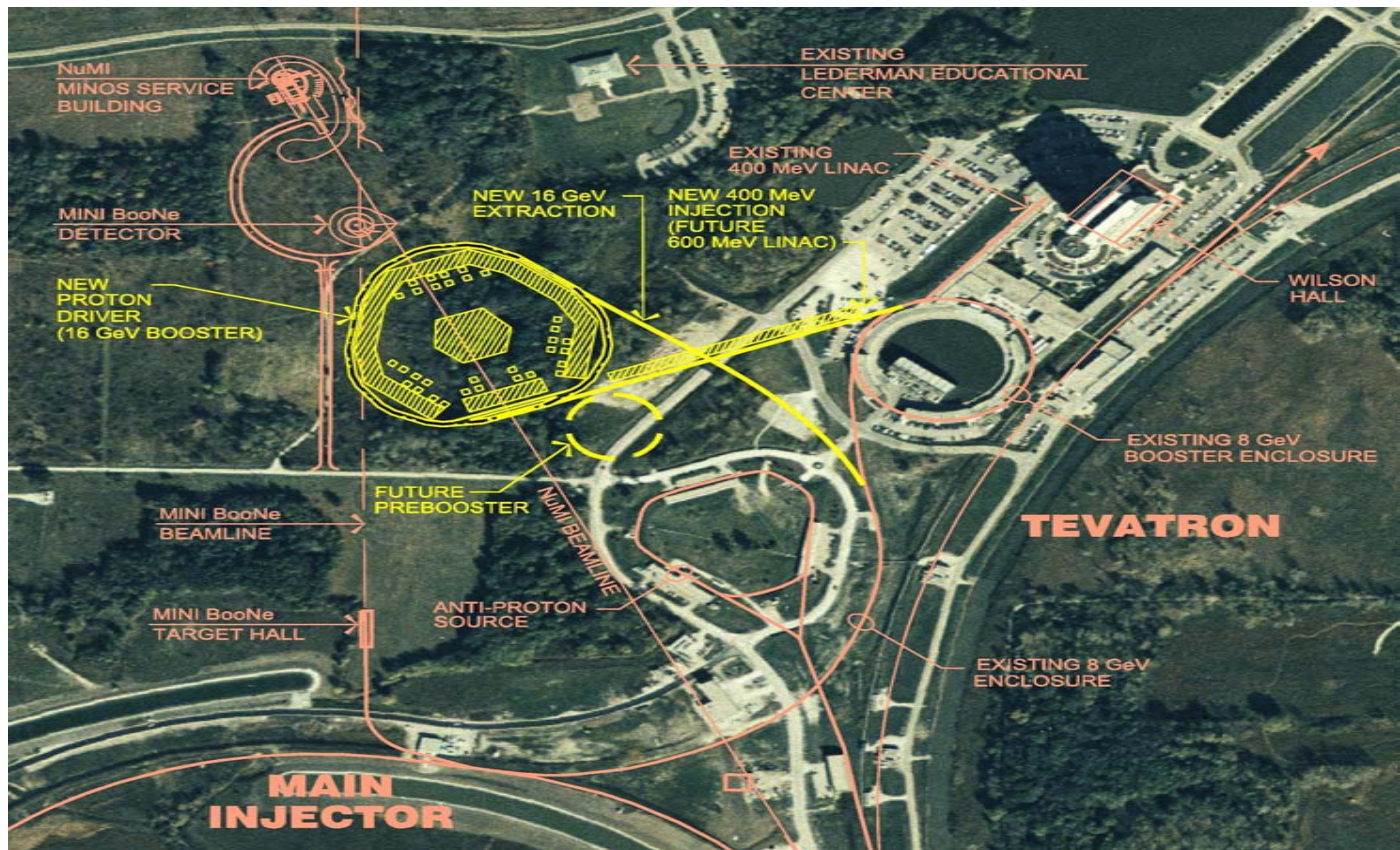
Outline

- ◆ **Topic A: An 8-GeV proton driver synchrotron**
 - Design, power and cost
 - R&D plan
- ◆ **Topic B: Improvement of the existing linac**
 - Front end and tank 1 (10 MeV)
 - Low energy section (116 MeV)
 - High energy section (313 – 500 MeV)
- ◆ **Topic C: 2-MW Main Injector upgrade**
- ◆ **Conclusions**

<http://www-bd.fnal.gov/pdriver/8GEV/>

Proton Driver Study I: 16 GeV

(Fermilab-TM-2136, December 2000)

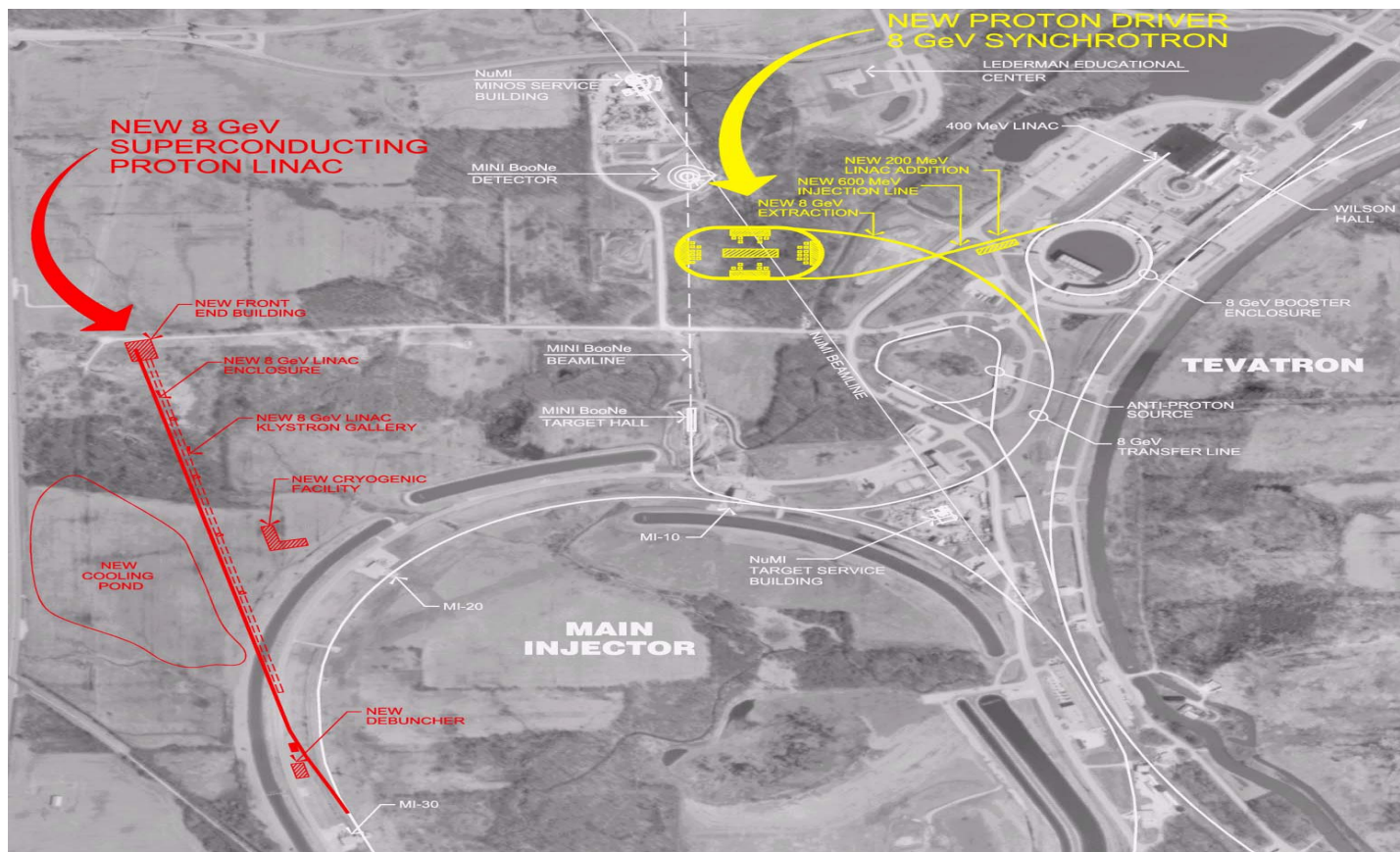


Charge from the Director

January 10, 2002

- ◆ The charge requested a design report consisting of the following parts:
 - An 8-GeV sc linac based proton driver (Bill Foster's talk)
 - An 8-GeV synchrotron based proton driver (this talk)
 - A 2-MW upgrade of the Main Injector (this talk)
- ◆ Part 1 of the report (8-GeV synchrotron and MI upgrade) was completed and published in May 2002.
- ◆ Part 2 (8-GeV sc linac) was finished recently.
- ◆ We are in the process of combining the two together into a single document.

Proton Driver Study II: 8 GeV (Fermilab-TM-2169)



Proton Driver Parameters

Parameters	Present Proton Source	Proton Driver (PD2)
Linac (operating at 15 Hz)		
Kinetic energy (MeV)	400	600
Peak current (mA)	40	50
Pulse length (μs)	25	90
H ⁺ per pulse	6.3×10^{12}	2.8×10^{13}
Average beam current (μA)	15	67
Beam power (kW)	6	40
Booster (operating at 15 Hz)		
Extraction kinetic energy (GeV)	8	8
Protons per bunch	6×10^{10}	3×10^{11}
Number of bunches	84	84
Protons per cycle	5×10^{12}	2.5×10^{13}
Protons per hour	9×10^{16} (@ 5 Hz)	1.35×10^{18}
Normalized transverse emittance (mm-mrad)	15π	40π
Longitudinal emittance (eV-s)	0.1	0.2
RF frequency (MHz)	53	53
Average beam current (μA)	12	60
Beam power (MW)	0.033 (@ 5 Hz)	0.5

Proton Driver Cost Estimate

1	Technical Systems			98,986
1.1	8 GeV Synchrotron		78,997	
1.2	Linac Improvements and Upgrade		17,500	
1.3	600 MeV Transport Line		900	
1.4	8 GeV Transport Line		1,589	
2	Civil Construction			37,152
2.1	8 GeV Synchrotron		17,500	
2.2	Linac extension		2,500	
2.3	600 MeV Transport Line		1,800	
2.4	8 GeV Transport Line		2,200	
2.5	Site work		4,800	
2.6	Subcontractors OH&P		5,760	
2.8	Environmental controls and permits		2,592	
	Total Direct Cost			136,138
	EDIA (15%)			20,421
	Lab Project Overhead (13%)			20,353
	Contingency (30%)			53,073
	Total Estimated Cost (TEC) (\$k)			229,985
	(in FY02 dollars)			

Notes to the Power and Cost

- ◆ Such a PD would bring the MI beam power to 2 MW. So the total beam power (PD + MI) would reach 2.5 MW. This should be compared with the present MI beam power of 0.3 MW.
- ◆ Besides, the proton driver itself can be increased from 0.5 to 2 MW with a “modest” linac energy upgrade from 600 MeV to 1.9 GeV (space reserved between the linac and the new ring).
- ◆ A fair comparison between different design options (e.g., linear vs. circular) is the total direct cost, which is \$136M for the synchrotron. The TEC depends on the cost model.
- ◆ Our cost model (EDIA, overhead, contingency) is the same as that in the BNL proton driver report. Fermilab’s total (\$230M for PD, \$36M for MI upgrade) is \$266M for 2.5 MW. (SNS: \$1.3B for 1.4 MW)

Proton Driver R&D Plan

- ◆ One feature of the Proton driver synchrotron R&D is that it is closely related to Run2, because it helps improve the existing machine performance.
- ◆ For example, the three major Booster projects during this shutdown are to large extent spin-offs of the proton driver study.
 - Collimators
 - Doglegs
 - RF cavity modification
- ◆ Proton Driver R&D for FY04:
 - Dual harmonic power supply test in E4R
 - Laser chopping
 - Space charge study
 - Inductive inserts
 - Warm magnet R&D
 - SC AC magnet R&D (*Superconducting PD synchrotron*)
 - New beam pipe prototyping

Booster New Collimator in L-5 and L-6

(N. Mokhov, A. Drozhdin, P. Kasper et al.)



Booster Dogleg Layout Modification in L-3

(J. Lackey, A. Drozhdin et al.)



Old layout, 18" spacing



New layout, 40" spacing

Booster RF Cavity Modification in L-15

(J. Reid)



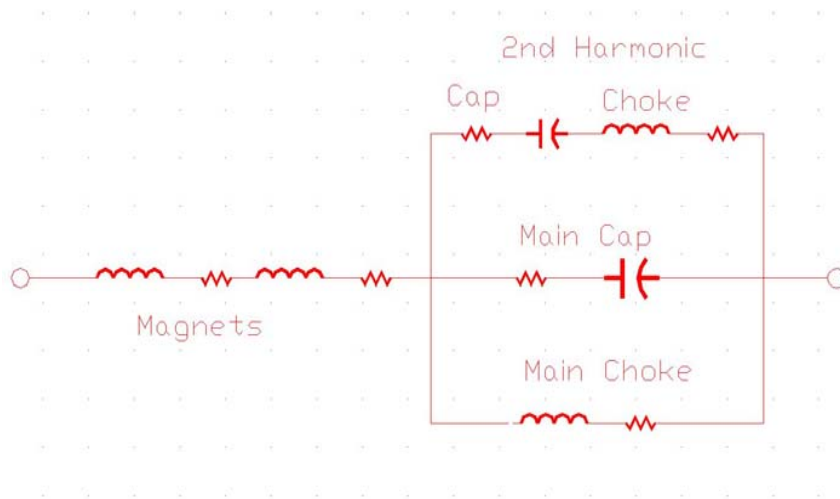
- ◆ Booster RF will be reused with modifications:
 - To increase the aperture from 2-1/4 in. to 5 in.
 - To increase the gap voltage from 55 kV to 66 kV.
- ◆ Two (out of 18) cavities have been modified and will be installed in the Booster soon.

Dual Harmonic Power Supply Test

(D. Wolff, D. Harding)

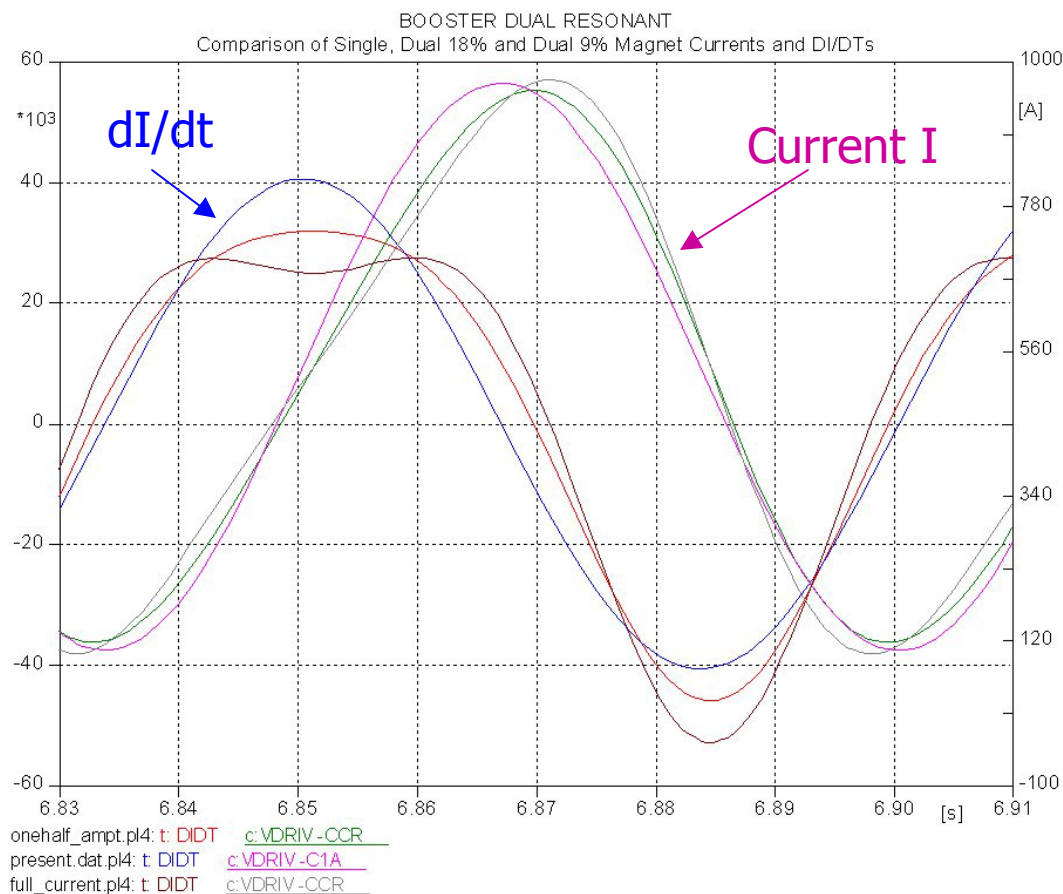
$$B(t) = \overset{\text{DC}}{\downarrow} B_0 - \overset{15 \text{ Hz}}{\downarrow} B_1 \cos(2\pi ft) + \overset{30 \text{ Hz}}{\downarrow} B_2 \sin(4\pi ft)$$

- $B_2 = 12.5\% B_1$
- Peak RF power ($\propto dI/dt$) reduced by 25%
- Test at E4R

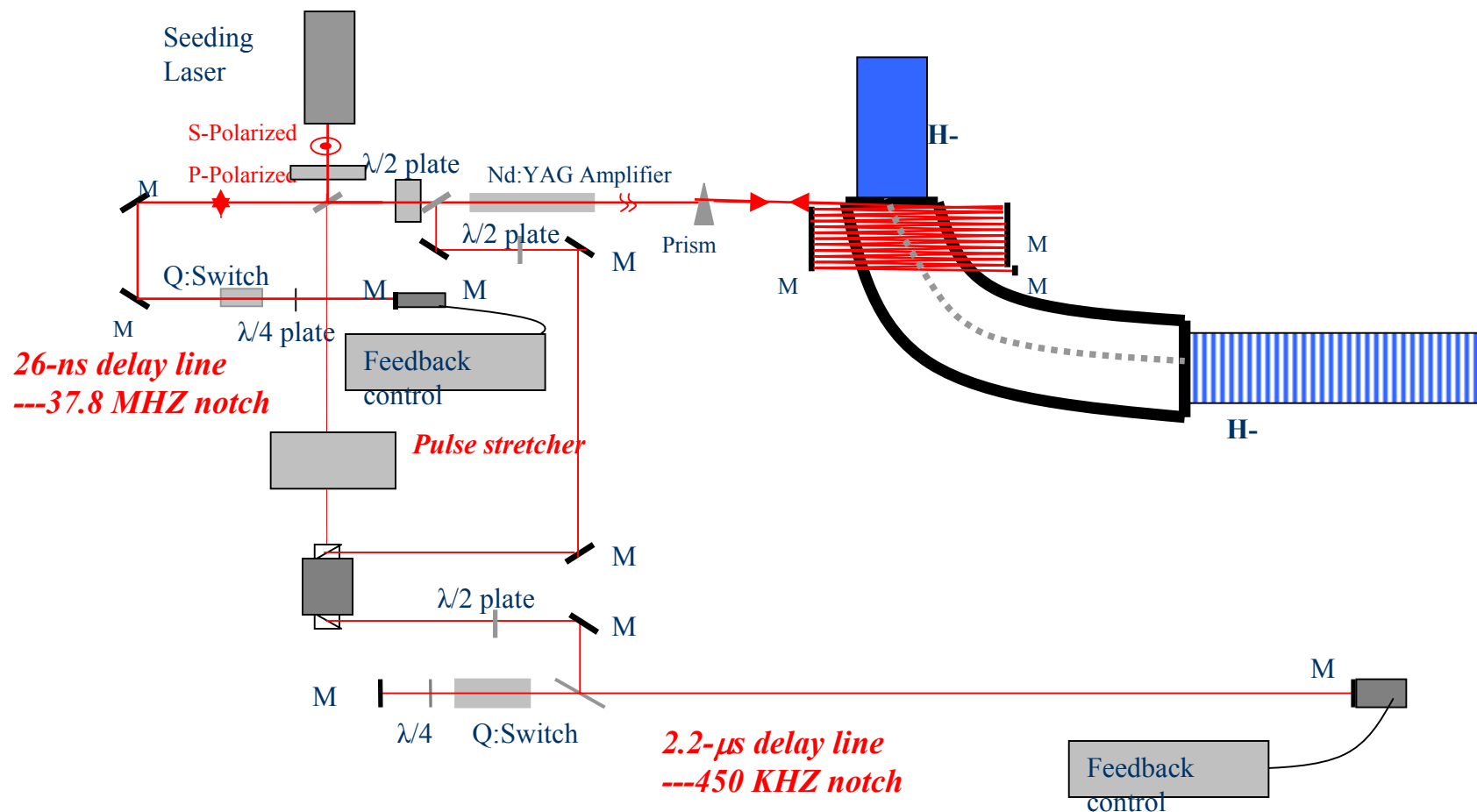


Dual Harmonic Current and dI/dt

(D. Wolff, 3 cases: dual 0%, 9%, 18%)

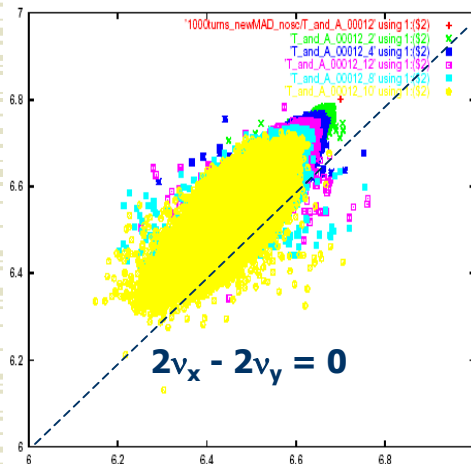


(R. Tomlin, X. Yang)

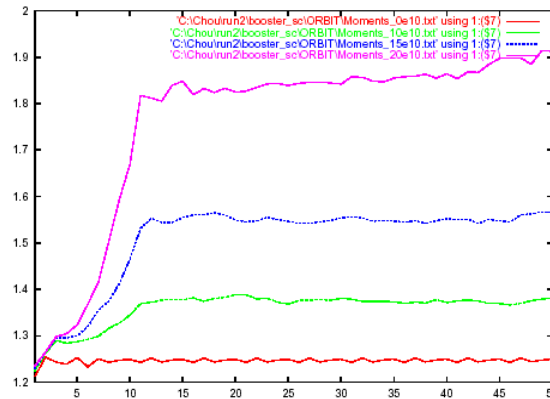


Space Charge Study

Tune shift



Emittance growth



Numerical simulations:

- ESME (P. Lucas, J. MacLachlan)
- ORBIT (F. Ostiguy, L. Michelotti, W. Chou; J. Holmes, ORNL)
- Track2D (C. Prior, RAL)
- Synergia (P. Spentzouris, J. Amundson)

Inductive Inserts

(D. Wildman, J. Lackey)

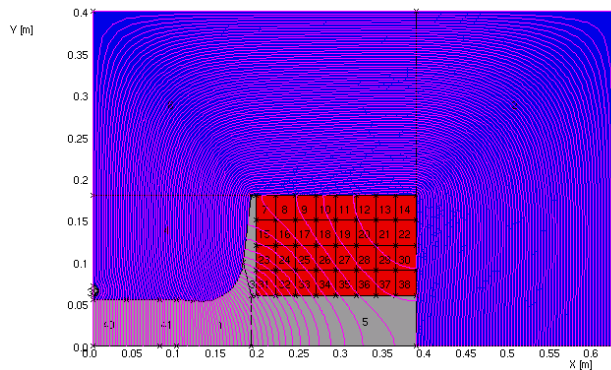


- ◆ For compensating space charge
- ◆ Test will be done in the Booster
 - Two modules have been tested, but inductance too low
 - A total of seven modules have been made and will be installed

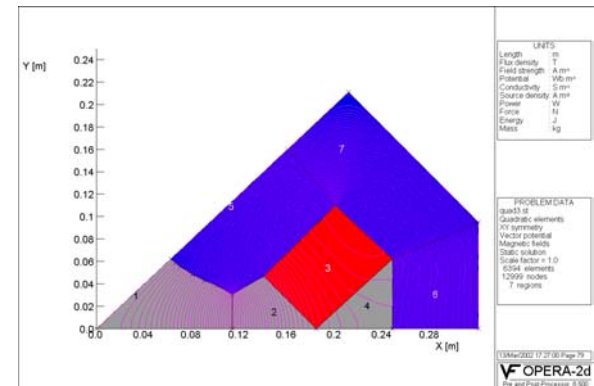
Warm Magnet R&D

(D. Harding et al.)

Dipole



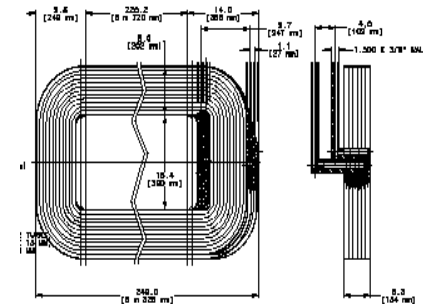
Quadrupole



Stranded conductors



Standard conductors with parallel connection



Superconducting AC Dipole Magnet (V. Kashikhin)

Main Issue:

Superconducting cable and winding with low eddy current losses

Magnet Parameters:

Magnetic field **1.5 – 3.0 T**

Frequency **15 Hz**

Air gap **100 – 150 mm**

Length **5.72m – 2.86 m**

Superconductor **NbTi/CuNi or HTS**

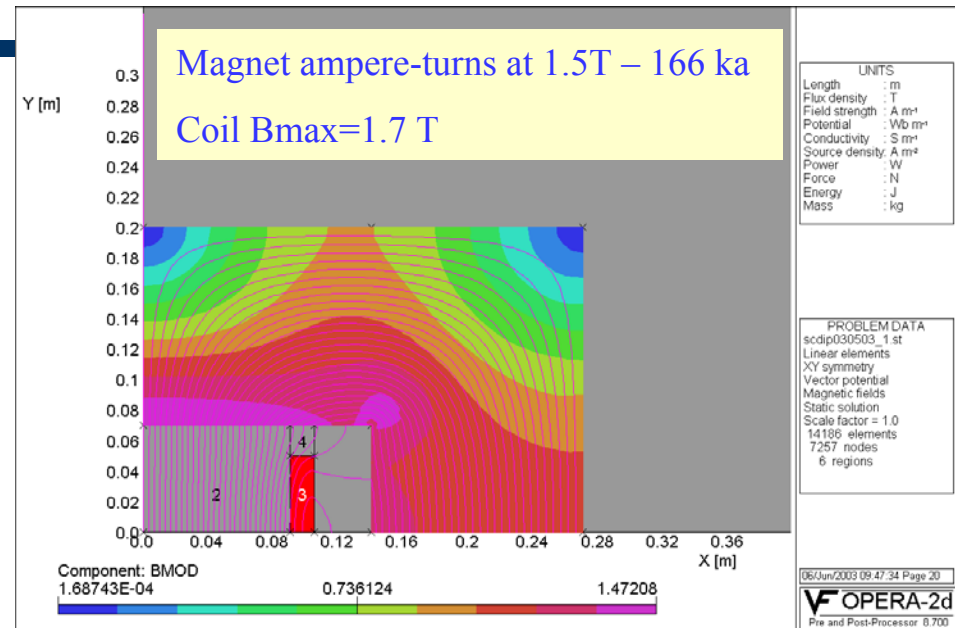
Iron/air core **room temperature**

Cooling **LHe forced flow**

Superconductor AC losses **< 3.3 kW/m³**
at 15 Hz and 0.5 mm dia.

Losses for 1.5 T magnet **1.2 W/m**
for NbTi/CuNi ALSTHOM superconductor
with 0.16 μ m filaments

Hysteresis losses can be effectively reduced by
decreasing a filament size up to ~ **0.2 μ m**

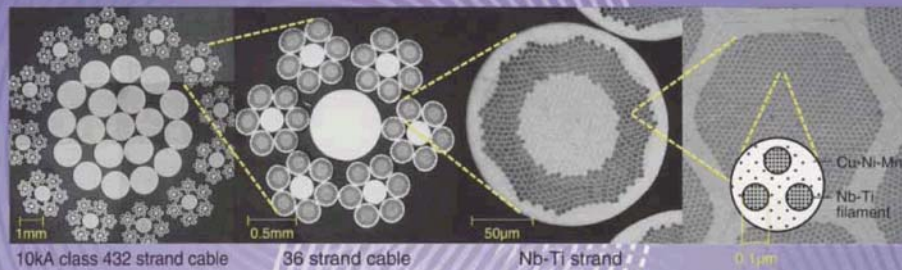


Eddy current losses effectively reduced by using high resistive CuNi matrix and small twist pitch 1.5mm for sub-wire and 6-8mm in 0.5mm wire.

Careful optimization needed between SC cable, cooling pipes/channels and construction elements to reduce heat load up to reasonable value

New AC NbTi superconductors (V. Kashikhin, R. Yamada)

High current density and low A.C. loss Superconducting cables and strands for A.C. application



- **Hitachi** gave us samples of AC superconductor with **0.1 µm** diameter filaments in Cu-Ni-Mn matrix
- **Furukawa** and **Bochvar** Institute will also send the samples after paper work
- **“Free” test stand** for 50 Hz sc cable available from **AIST (Japan)**

High A.C. field, low A.C. loss and large clear bore diameter A.C. superconducting magnets and power applications



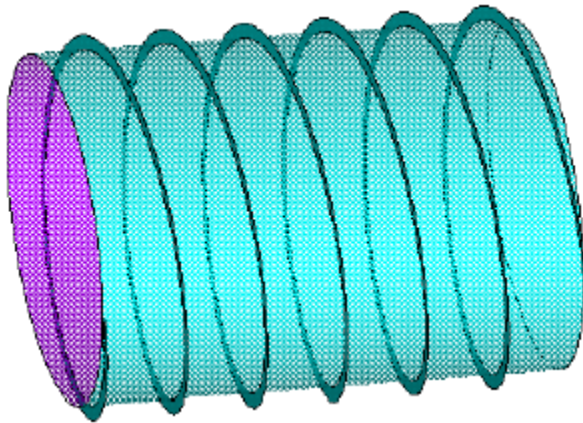
Features

- cable and strand
 - 10kArms class large current capacity Nb-Ti superconducting cable for A.C. application
 - 432 strand cable diameter: 10mm, strand diameter: 0.2mm
 - Ultra super fine superconducting filament (0.1µm) and Cu-Ni-Mn alloy matrix (Low A.C. loss)
 - 5kArms class bronze processed Nb₃Sn superconducting cable
- Magnet and power application
 - Large capacity A.C. superconducting magnet (>1MVA, ~2T, >150mm clear bore)
 - A.C. superconducting split magnet
 - Nb₃Sn R&W A.C. magnet
 - Superconducting fault current limiter
 - Superconducting transformer

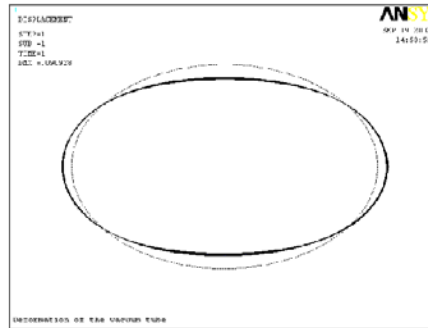
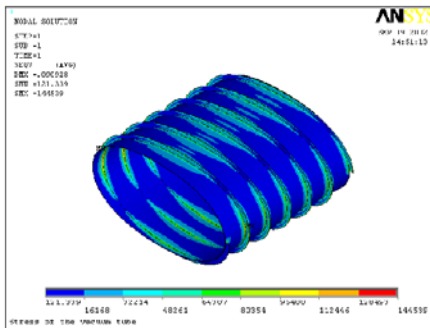
HITACHI

New Beam Pipe for RCS

(Z. Tang, A. Chen, W. Chou)



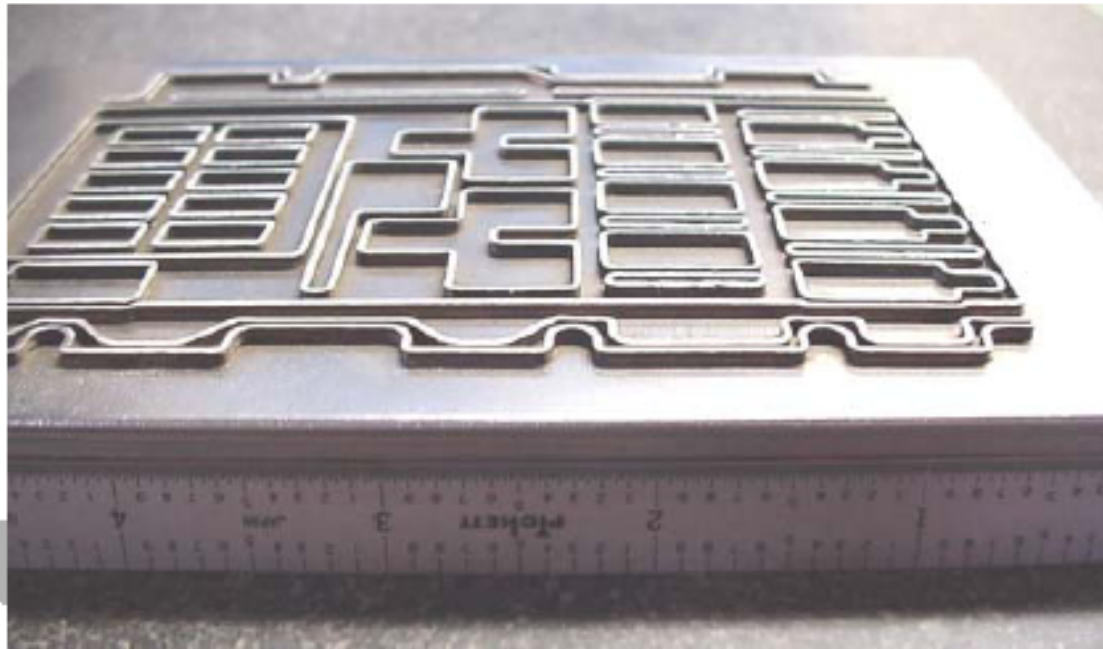
- ◆ Design: thin metallic pipe reinforced by spiral ribs
- ◆ Aperture: 4 in x 6 in oval
- ◆ Material: Inconel 718
- ◆ Wall thickness: 8 mils (0.2 mm)
- ◆ Spiral ribs: rectangular cross-section, width 28 mils, height 18 mils, 10 layers (total height 0.18 inch)
- ◆ Welding technique: laser deposition



Laser Precision Metal Deposition

(courtesy H&R Technology Inc.)

**Cutting die prior to sharpening;
Die Base: Carbon Steel, Knife Pattern: 420 SST**



R&D Budget Request for FY04 (M/S part)

♦ Dual harmonic power supply test	\$45 k
♦ Laser chopping	\$38 k
♦ Inductive inserts	\$ 6 k
♦ Warm magnet R&D	\$60 k
♦ AC sc magnet development	\$50 k
♦ Thin metallic pipe	\$60 k

Total R&D request for FY04: \$259 k
(0.1% of the construction cost)

Topic B: Improvement of the Existing Linac

- ◆ Linac improvement:

This is the "common denominator" of the two proton driver options (linear or circular) and can go ahead regardless which option would be chosen.

- ◆ There are three choices: (choose as many as you wish)

(1) New 201 MHz front end & Tank 1 (10 MeV):

To improve H^- beam brightness by a factor of 3.

(2) New 402 MHz low energy section (116 MeV):

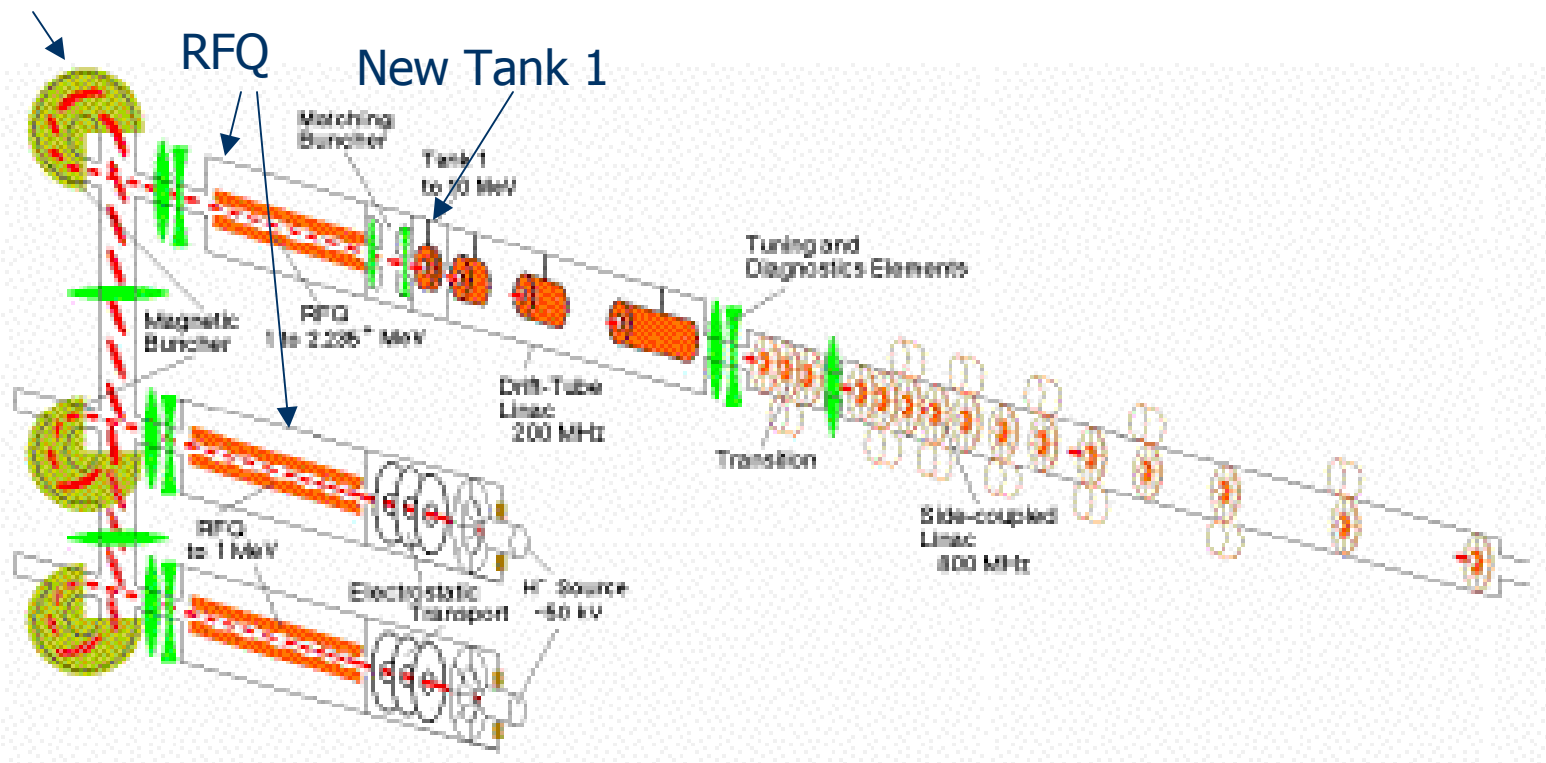
To solve the 7835 tube supply problem.

(3) New 805 MHz sc high energy section (313-500 MeV, replacing CCL no. 6 and 7):

To increase Booster beam intensity by 20%.

(1) Linac New Front End & Tank 1 (10 MeV)

Alpha magnet



(2) New 402 MHz Low Energy Section (116 MeV)

				DTL			CCL	
	RFQ	Tank 1	Tank 2	Tank 3	Tank 4	Match Section	Mod 1	Mod 2
MeV	0.035	3	13.4	32.9	51.6	70.3	70.3	93.3
MeV	3	13.4	32.9	51.6	70.3	70.3	93.3	116.5
MeV	2.965	10.4	19.5	18.7	18.7	0	23	23.2
mA	70	55	55	55	55	50	50	50
MHz	402.5	402.5	402.5	402.5	402.5	805	805	805
usec	90	90	90	90	90	90	90	90
usec	130	130	130	130	130	125	125	125
Hz	15	15	15	15	15	15	15	15
	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
MV/m		2.4 to 4.6	4.6	4.6	4.6	7.5 to 7.35	8	8
m		4.5	6	6.1	6.2	3.25	4.8	4.9
MW		1	1.75	2	2		5.4	5.4
MW		0.63	1.07	1.02	1.02		1.38	1.39
MW		2.5	3.8	4	4		8.5	8.5

(3) New 805 MHz SC High Energy Section (313 – 500 MeV)

- ◆ Retain the existing CCL stations No. 1-5 for accelerating the beam to 313.6 MeV.
- ◆ Replace the last two CCL stations No. 6-7 by SNS-type $\beta=0.81$ sc cavity for an energy upgrade to 500 MeV.
- ◆ The requires a “real estate” gradient of 9.5 MV/m in a 19.5 m long space, which is feasible.
 - The peak field is 35 MV/m, already achieved by the SNS
 - The fill factor is 0.63, which will require some changes in the SNS design (using quadrupole doublet, replacing SNS input coupler by TESLA type)

Linac Improvement Cost Estimate

- ♦ New 200 MHz front end & Tank 1 (10 MeV) \$4M
- ♦ New 402 MHz low energy section (116 MeV) \$27.6M (incl. \$4M)
- ♦ New 805 MHz sc high energy section (313 – 500 MeV) (TBD)

Topic C: 2-MW Main Injector Upgrade

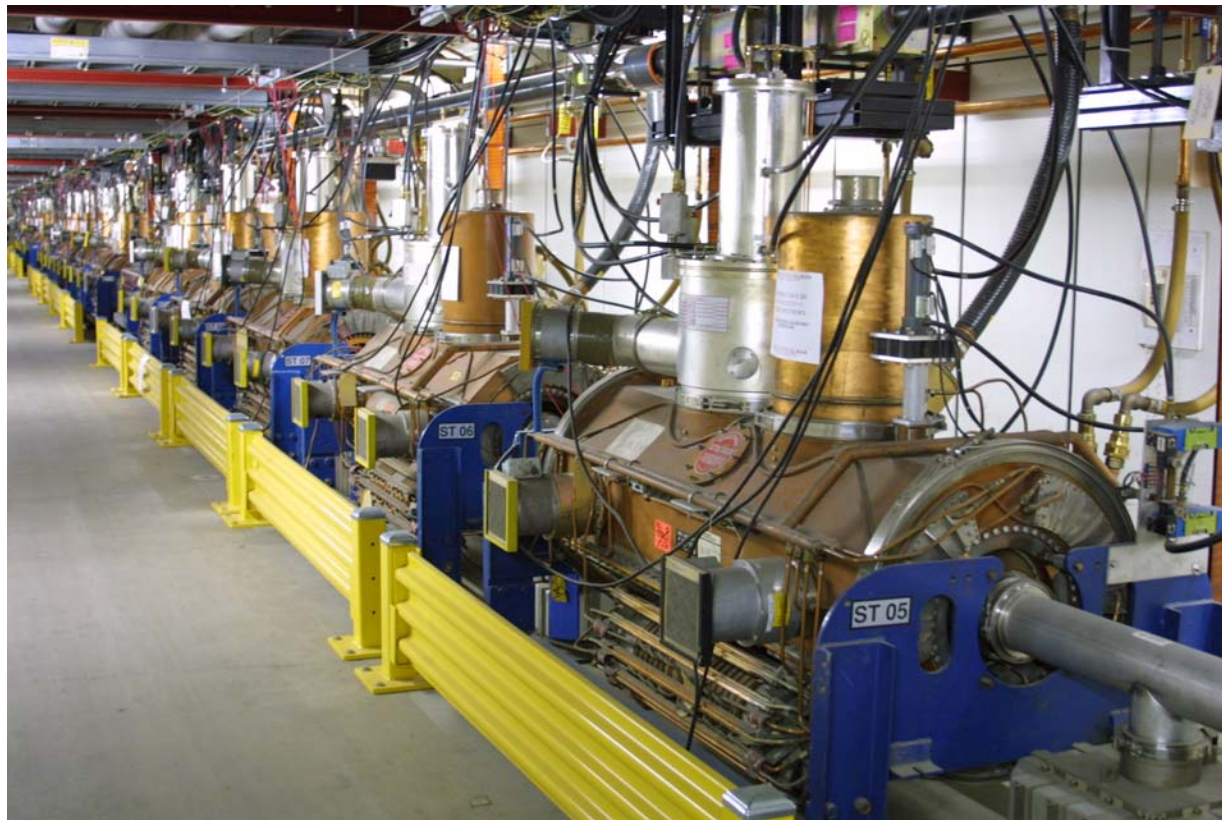
- Increase beam intensity by a factor of 5
- Reduce cycle time by 20%
- Increase beam power by a factor of 6

	Present MI	Upgraded MI
Injection kinetic energy (GeV)	8	8
Extraction kinetic energy (GeV)	120	8 - 120
Protons per MI cycle	3×10^{13}	1.5×10^{14}
Cycle time at 120 GeV (s)	1.867	1.533
Beam power (MW)	0.3	1.9

Technical System Upgrade

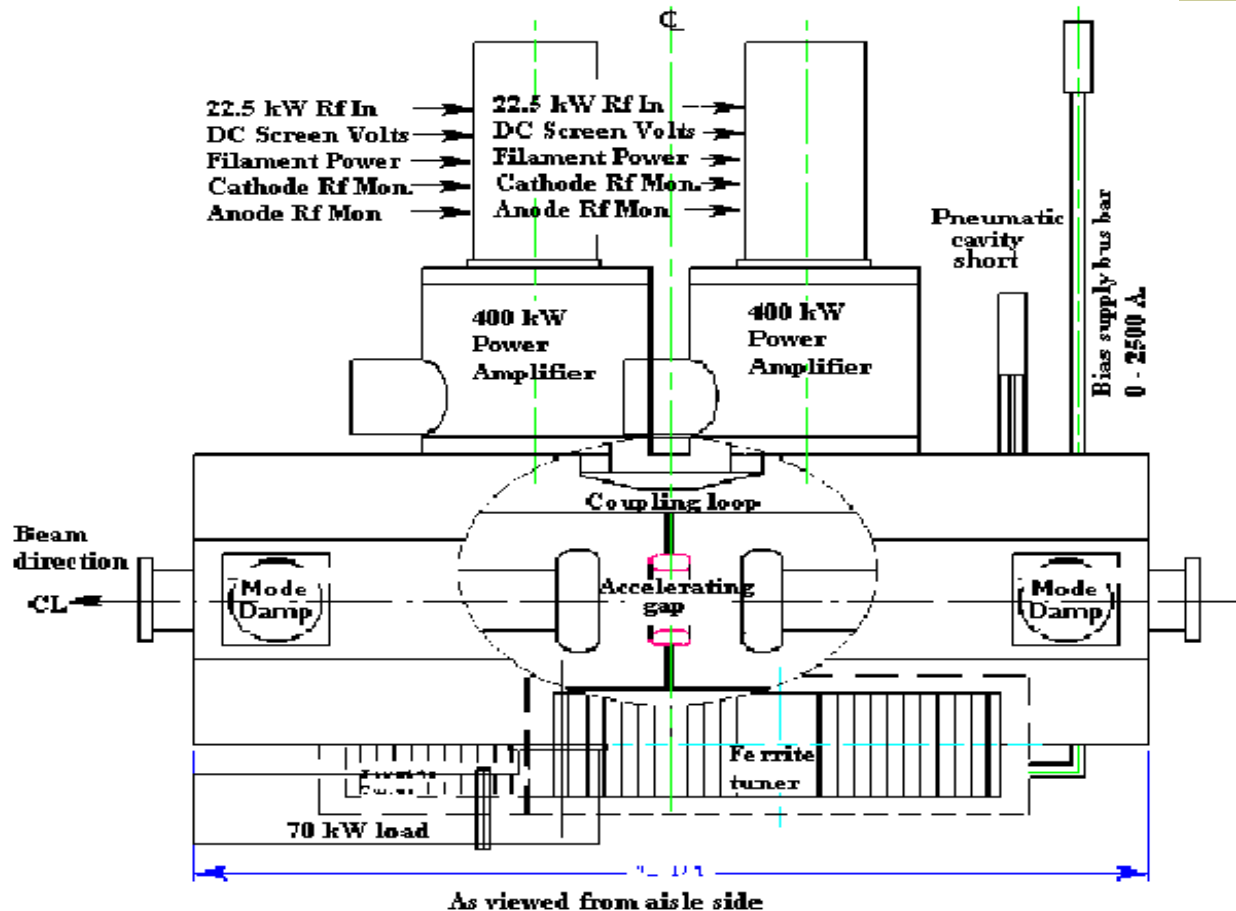
- ♦ One major upgrade:
 - RF system
- ♦ Several moderate upgrades:
 - Magnet power supply
 - Kickers
 - Feedback and damper
 - Beam dump
 - Cooling
 - NuMI and MiniBooNE beam lines
- ♦ Three new systems:
 - Gamma-t jump
 - Large aperture quadrupole (LAQ)
 - Collimators
- ♦ No need for upgrade:
 - Magnet (But the recycled Main Ring quads may need to be replaced for reliability reason)
 - Shielding
- ♦ Two additional upgrades for sc linac option:
 - 8 GeV H^- injection
 - MiniBooNE beam line

Main Injector RF System



RF Upgrade – Dual Power Amplifier

(J. Griffin, D. Wildman, J. Reid)

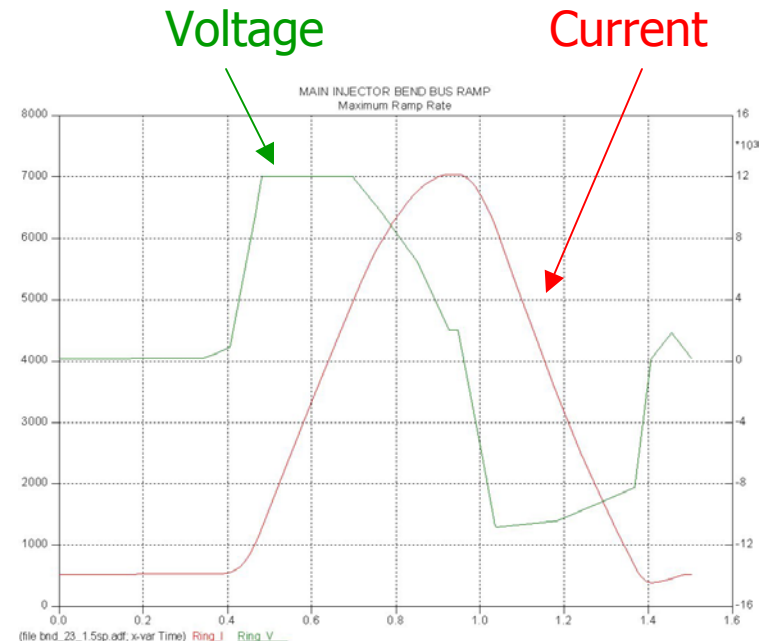


Magnet Power Supply for 1.5 sec Cycle (*)

(D. Wolff)

Today's max Pdot is 240 GeV/s, upgrade to 305 GeV/s

Time	Momentum	Pdot	Pddot
<u>0.34000</u>	8.889	0.00	0.00
<u>0.36367</u>	8.96	6.00	253.52
<u>0.40521</u>	9.5	20.00	337.04
<u>0.48213</u>	22	305.00	3705.00
<u>0.69862</u>	85	277.00	-129.33
<u>0.84938</u>	115	121.00	-1034.80
<u>0.92706</u>	119.7	0.00	-1557.55
<u>0.94706</u>	119.7	0.00	0.00
<u>1.03615</u>	105	-330.00	-3704.08
<u>1.17901</u>	60	-300.00	210.00
<u>1.36747</u>	11	-220.00	424.49
<u>1.40656</u>	6.7	0.00	5627.91
<u>1.45521</u>	7.7945	45.00	925.08
<u>1.50385</u>	8.889	0.00	-925.08
<u>1.50485</u>	8.889	0.00	0.00

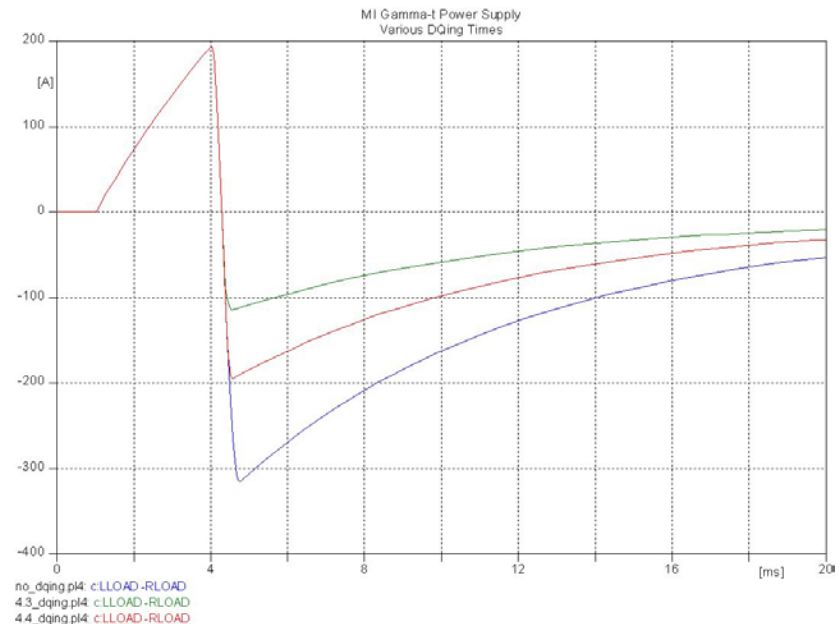


(*) A more aggressive upgrade for 1 sec cycle has also been studied.

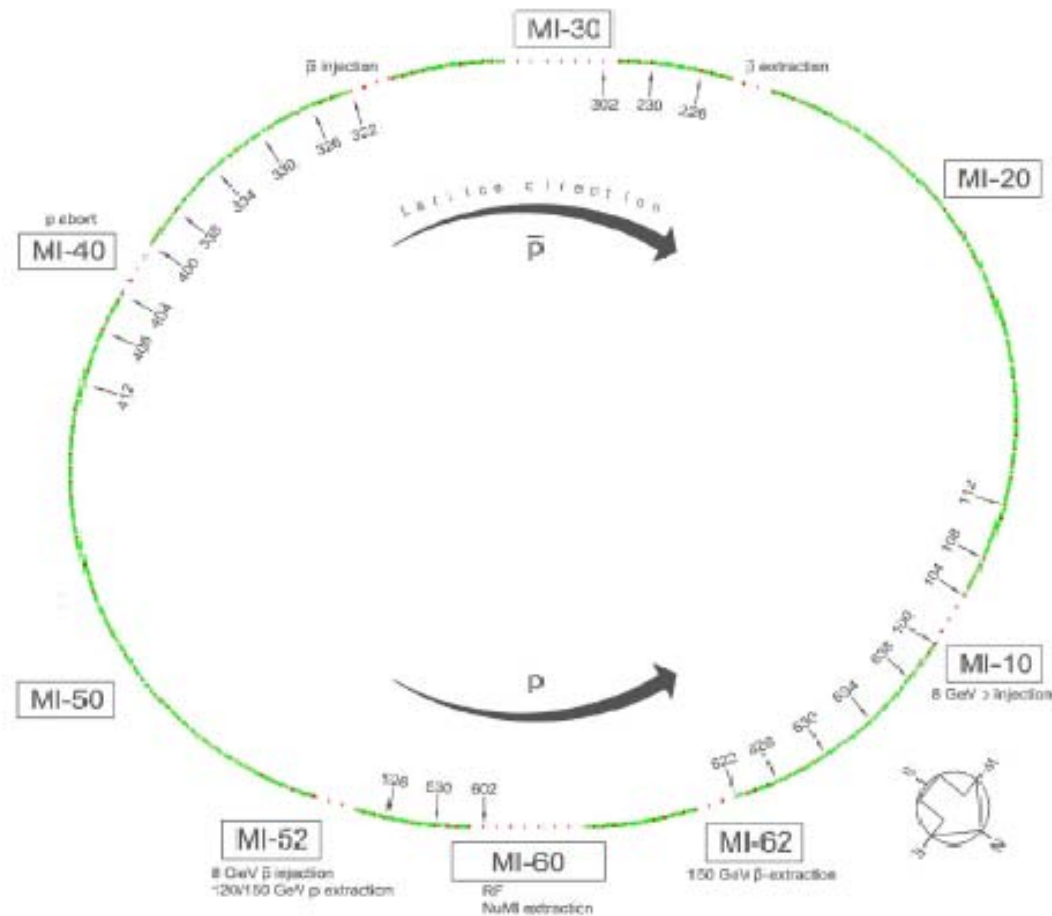
New Gamma-t Jump System

(W. Chou et al.)

- ◆ A first order jump system with small dispersion increase (taking advantage of the dispersion free region)
- ◆ Design goal:
 - $\Delta\gamma_T = \pm 1$ within 0.5 ms
 - $d\gamma/dt = 4000$ 1/s
 - 16 times faster than the normal ramp (240 GeV/s)



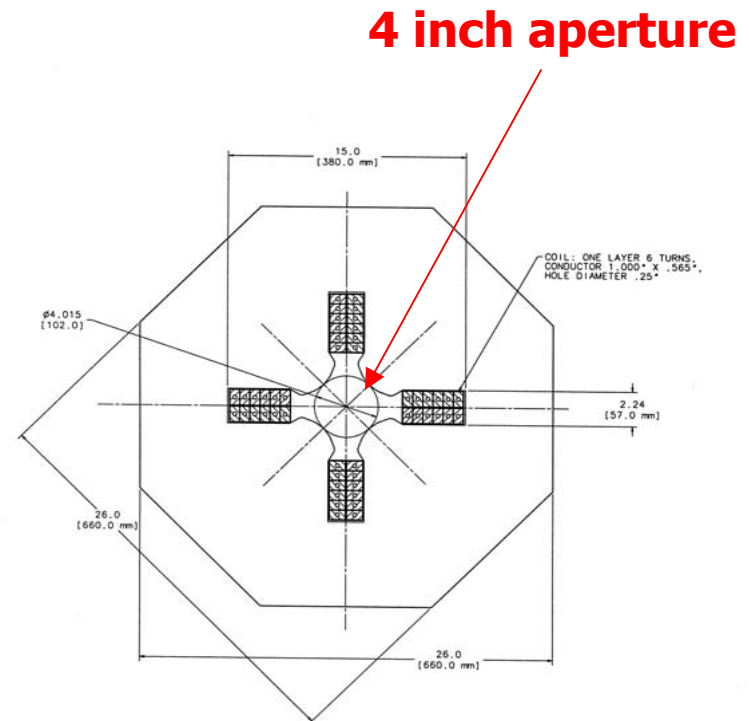
Gamma-t Jump System Layout



New Large Aperture Quadrupoles (LAQ)

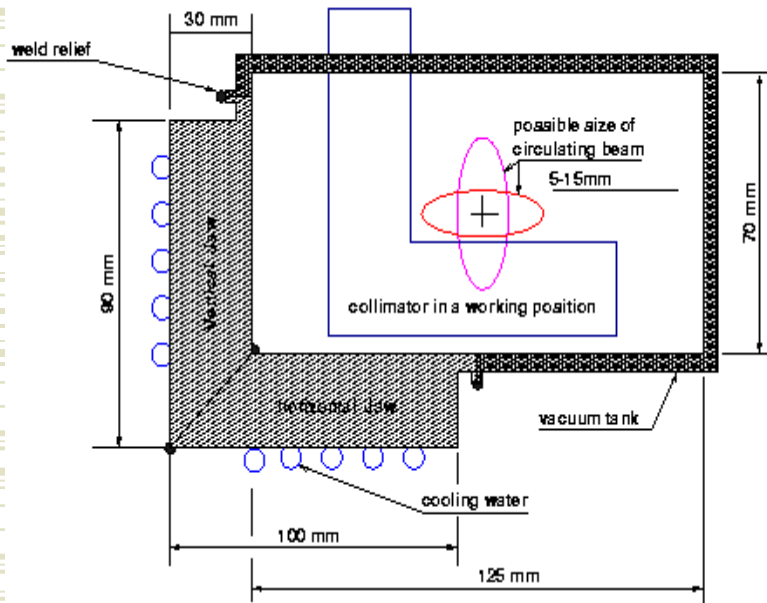
(V. Kashikhin)

- ◆ In injection and extraction sections, the quads near the Lambertson limit the physical aperture.
- ◆ They will be replaced by large aperture quadrupoles (LAQ)
- ◆ Regular quad: 83.48 mm
LAQ: 102.24 mm

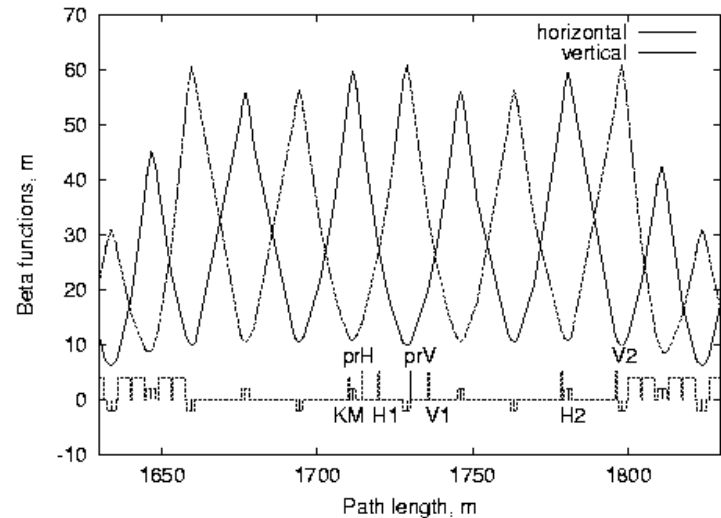


New Collimation System in MI-30

(A. Drozhdin)



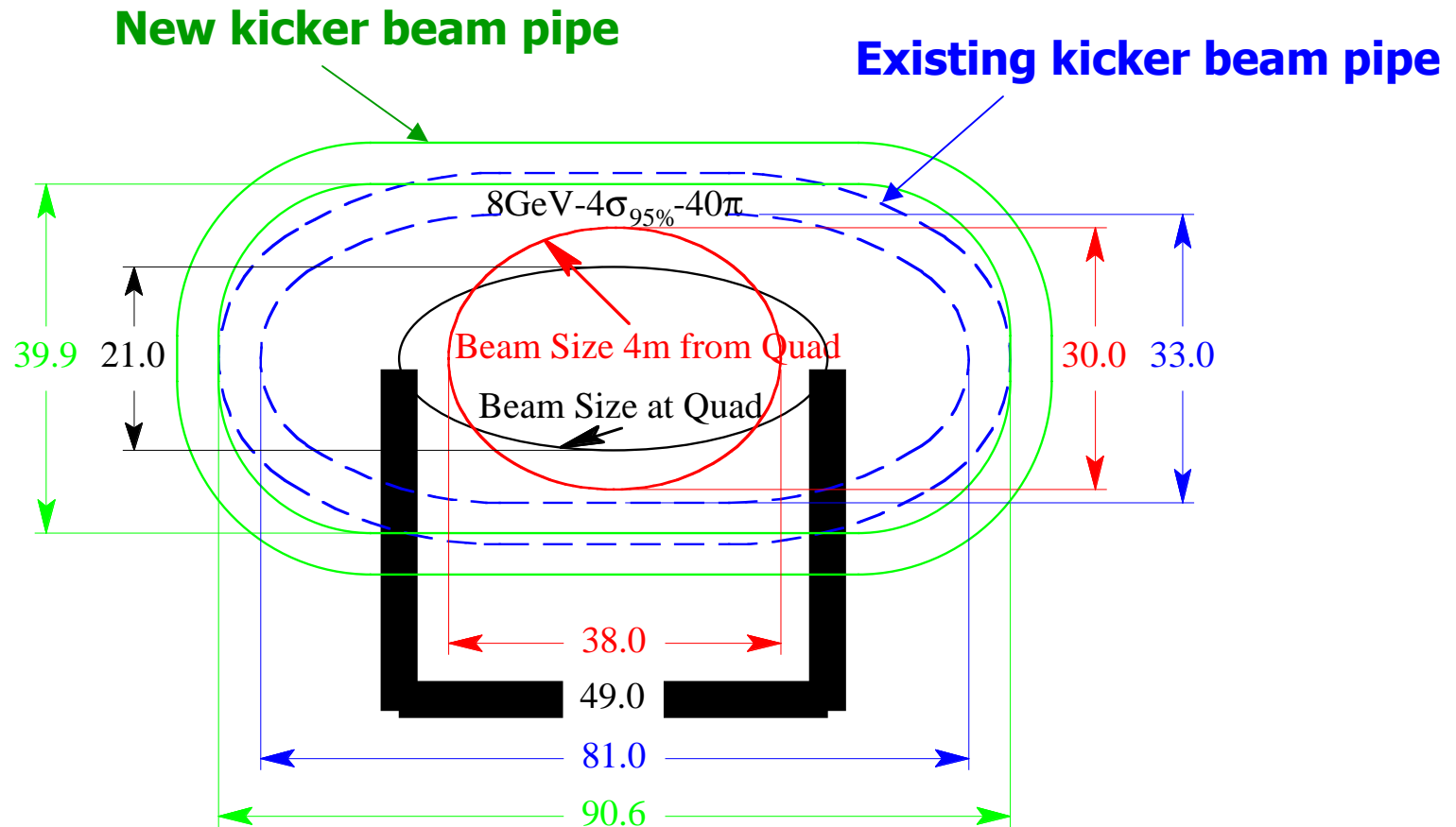
Secondary collimator cross section



Primary and secondary collimators location and beta function in the MI-30 straight section

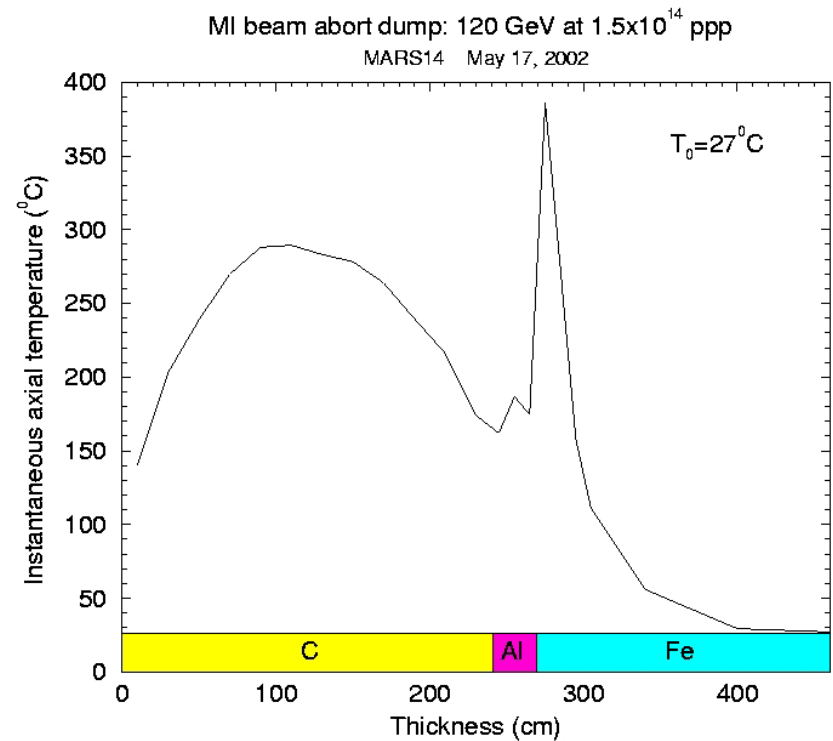
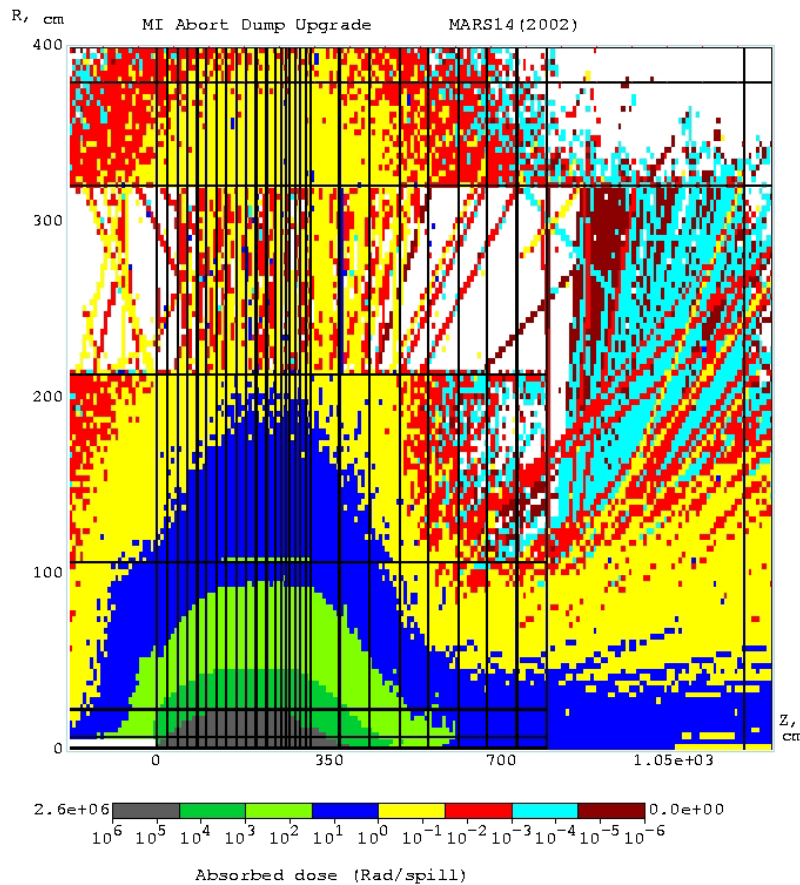
Kicker System Upgrade

(C. Jensen)



Beam Dump Upgrade in MI-40

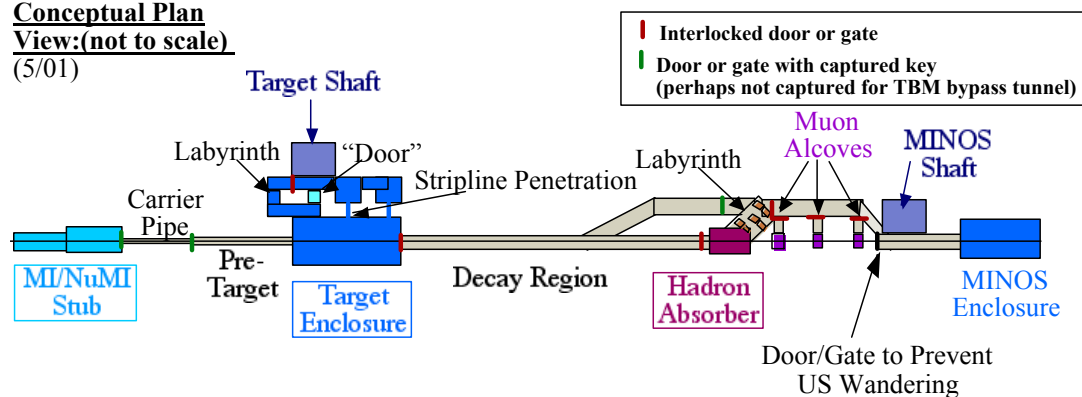
(N. Mokhov)



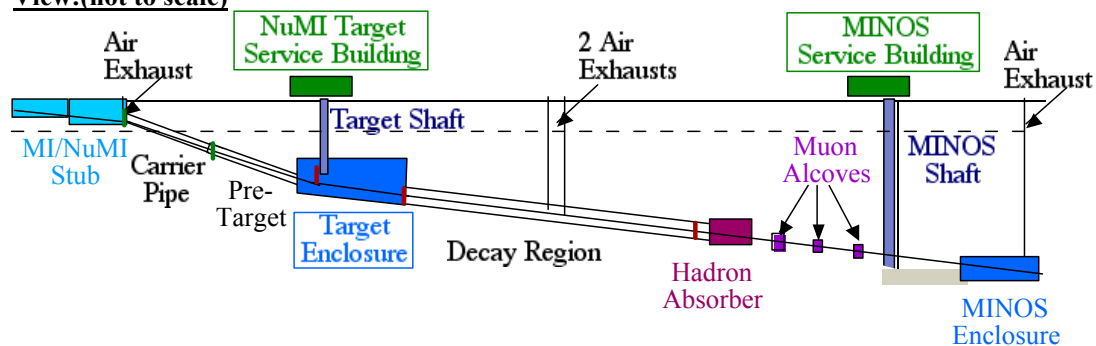
NuMI Beamline Upgrade

(N. Grossman, D. Harris)

Conceptual Plan
View:(not to scale)
(5/01)



Conceptual Elevation
View:(not to scale)



Two Additional Upgrades for SC Linac Option

- ◆ 8 GeV H^- injection in the MI:
 - Presently the injection is bucket-to-bucket proton transfer from the Booster.
 - When the 8 GeV sc linac is used as the injector, a new H^- injection system needs to be built in the MI.
- ◆ MiniBooNE beam line:
 - Presently the beam comes directly from the Booster via the MI-8 line.
 - The 8 GeV sc linac will need another beam line for MiniBooNE.
 - Some technical systems (e.g., the horn) will also need upgrade due to the long pulse of the sc linac (1 ms).
- ◆ Both are currently under study and not yet included in the following cost estimate.

MI and Beamline Upgrade Cost Estimate (*)

1	Main Injector Upgrade		23,502
1.1	RF system	14,238	
1.2	Main power supplies	430	
1.3	Gamma-t jump system	490	
1.4	Large aperture quadrupole	710	
1.5	Kickers	1,060	
1.6	Longitudinal feedback	625	
1.7	Collimators	325	
1.8	Beam dump	500	
1.9	Controls	303	
1.10	Utilities	1,406	
1.11	ED&I	3,415	
2	NuMI Beamline Upgrade		8,920
3	MiniBooNE Beamline Upgrade		250
4	Project Management		3,000
	TOTAL (\$k)		35,672

(*) Not included are the 8-GeV H⁻ injection and MiniBooNE modification required by the sc linac option.

Conclusions

- ◆ The good news is that the proton driver made DOE's list on the 20-year roadmap. The bad news is its priority is rather low (tie for 21 out of 28).
- ◆ With a Proton Driver, Fermilab will get two high power proton facilities – the PD itself (0.5-2 MW), and a 2-MW Main Injector.
- ◆ The synchrotron construction cost is modest. It is even possible to get it done without a “budget bump” in the HEP program.
- ◆ In any event, the R&D for a synchrotron PD and MI will be a good investment – The money is small, but the return is big and immediate (useful for Run2). Some costs can also be absorbed by the Run2 upgrade plan.

Questions?
